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EFFECT OF INCLUDED MEDIA ON THERMAL CONDUCTANCE OF CONTACT JOINTS

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THERMAL CONDUCTANCE OF CONTACT JOINTS

by

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Submitted in partial fulfillment
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PREFACE

Whenever an engineer turns to the available literature for information concerning heat flow across a joint formed by two pieces of material in simple contact, he is apt to read a phrase similar to this,

> The resistance to the flow of heat between two solid surfaces in simple mechanical contact _is_ highly unpredictable.*

Thus the problem of thermal contact resistance which has concerned engineers for a century or more continues to be important in conventional design and may be the critical design factor in nuclear power work where extremely high heat fluxes are encountered. Yet, as Dr. Glasstone implies, much information remains still uncovered concerning heat flow across such an interface.

The objective of this thesis is to investigate the effect of different included media on the thermal conductance of contact joints formed between two solid surfaces in simple mechanical contact. The units employed in the experimental work were designed by the author. Work was done from January, 1956 through May, 1956 at the United States Naval Postgraduate School, Monterey, California.

The author is indebted to Professor C.P. Howard for his valuable guidance throughout the entire work and to Professors E. E. Drucker and C. D. G. King for their advice and assistance. Grateful acknowl-

*Glasstone, Samuel: Principles of Nuclear Reactor Engineering, D. Van Nostrand Company, Inc., 1955, p. 667.

edgement is due to Mr. R. P. Kennicott and Mr. A. B. Rasmussen for their excellent machine work and helpful suggestions in assembling the apparatus.

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TABLE OF SYMBOLS AND ABBREVIATIONS

(Listed in the order of their use in the text)

Q	-Heat flowing, B.T.U./hr.
k	-Thermal conductivity, B.T.U./ hr.-ft.^{2}-°F./ft.
A	-Cross-sectional area of the contacts, square feet
T	-Temperature, °F., subscripts locate the temperature with reference to the source end of the system
x	-Distance measured along the axis of the test cylinders, ft.
h	-Thermal conductance; computed at the interface, B.T.U./hr.-ft.^{2}-°F.
t_1, t_2	-Temperature, found by extrapolation from the source and sink ends, respectively, °F.
ΔT	-t_1-t_2, the temperature difference at the interface, °F.
T_m	-Temperature "level", the theoretical mean temperature of the interface, $\frac{1}{2}$ ($t_1 + t_2$)
P	-Axial load in pounds divided by the cross-sectional area, p.s.i.

SUMMARY

The objective of this thesis was to investigate the relative magnitudes of the thermal conductance coefficient, h, at the interface of two solid aluminum cylinders in simple mechanical contact when the included media at the interface were vacuum, air, and helium.

Vacuum, air, and helium were chosen as the included media because of their low, average, and high thermal conductivities, respectively. An apparatus was constructed to provide heat flow through aluminum test specimens pressed together with a known force at a known mean temperature level. Means were provided to introduce the media at the interface between the test specimens and to detect and record the temperatures at various locations in the test assembly. The thermal conductance coefficients were then computed using the available experimental data.

The following conclusions were drawn after analysis of the data:

a. The average thermal conductance at a joint between two solid aluminum cylinders in simple mechanical contact is in the ratio of 4.26-1.59-1.00 for helium, air, and vacuum as the included media when the pressure is varied from 100 p.s.i. to 300 p.s.i. and the mean temperature level is varied from 150°F. to 250°F.

b. No single mode of heat transfer is predominant in the mechanism of heat transfer across such a joint when a gas is the included medium.

c. There is further need for more work in the field before accurate predictions of thermal conductance coefficients can be made.

CHAPTER I

INTRODUCTION

The mechanism of heat transfer by steady unidirectional conduction is given by the simple relation that J. B. J. Fourier proposed in 1822. Fourier showed that for a perfectly insulated homogeneous isotropic solid bar between a thermal source and sink, the heat flux is given by:

$$Q = - kA \frac{dt}{dx} \qquad (1)$$

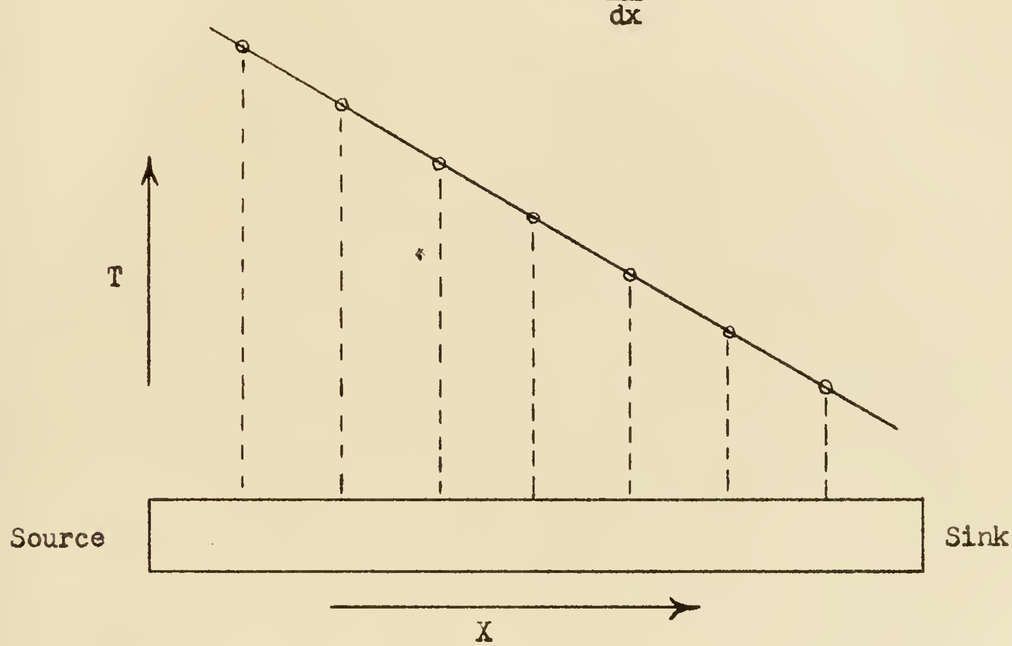


Figure 1

For two cylinders butted together the same heat flux must exist on each side of the interface. The temperature difference at the joint and the overall conductance may therefore be substituted in Equation (1):

$$h(\Delta T)A = kA \frac{dt}{dx} \qquad (2)$$

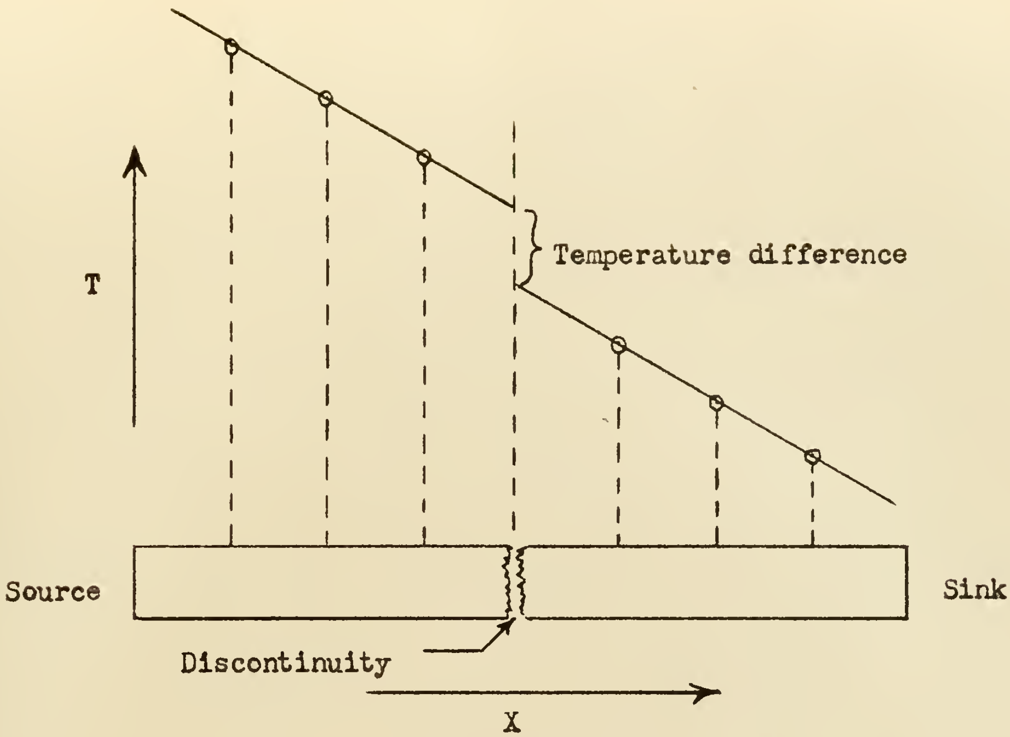


Figure 2

Thus the thermal conductance coefficient, h, may be computed by:

$$h = \frac{k \frac{dt}{dx}}{\Delta T} \qquad (3)$$

P. W. Bridgman (9)* has shown that even at very high pressures the thermal conductivity of the solid material is a function of the temperature and chemical composition. Hence, for a given metal for which $k = f(T)$ is known, the empirical solution of Equation (3) reduces to an accurate determination of temperature and thermocouple location. Mc Adams (8) warns that impurities may be the dominant

*Numbers in parentheses as hereinafter used refer to books, papers, and articles listed in the bibliography.

factor affecting the thermal conductivity of a solid. For this reason, the specimens were taken from the same bar.

A simplified mode of attack in analyzing heat flow across a joint between two solids in mechanical contact would be to make no allowance for a temperature drop at the boundary, which would presuppose perfect metal to metal contact. However, this requires the absense of gases or vacant spaces caused by those blowholes, bubbles, roughened surfaces, etc. which are very likely to be present when two surfaces are brought together. Even traces of poorly conducting material between metals, such as oxide films on the surface and dust specks, will cause abrupt drops in the temperature. Thus the thermal circuit must include contact resistance and will appear thusly:

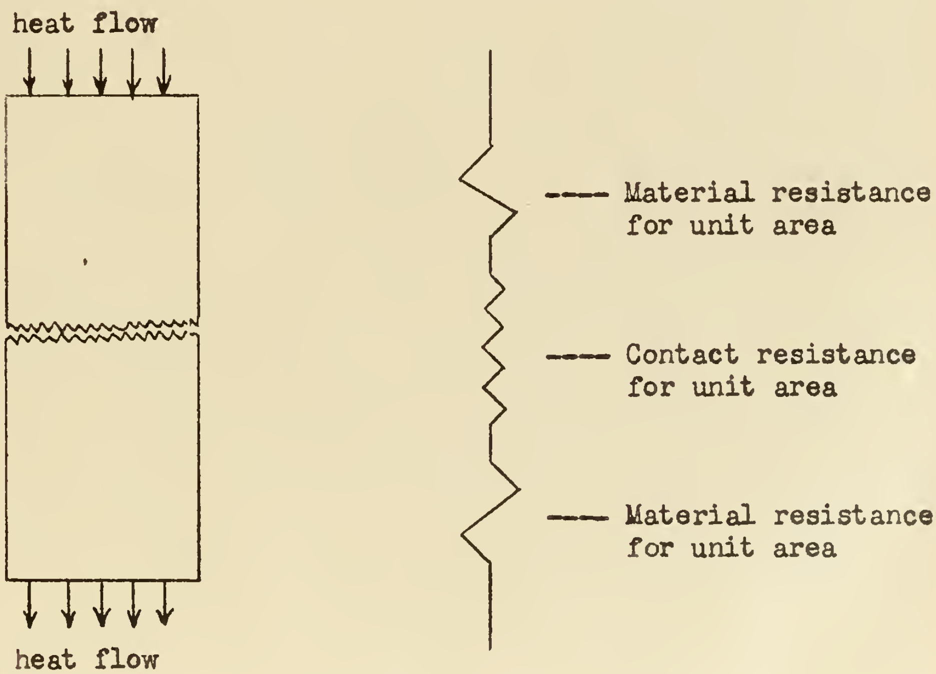


Figure 3

It is usually difficult to measure or even estimate with any accuracy the thickness of the gap between two solids in contact and the amount of metal in physical contact. J. D. Keller (5) estimates that only two to five percent of such surfaces are in actual metallic contact. Where the gap between two machined surfaces is so narrow that natural convection can be ignored, heat will be transferred by metallic conductance and by both radiation and conduction across the gap. The thermal circuit for the contact resistance then appears:

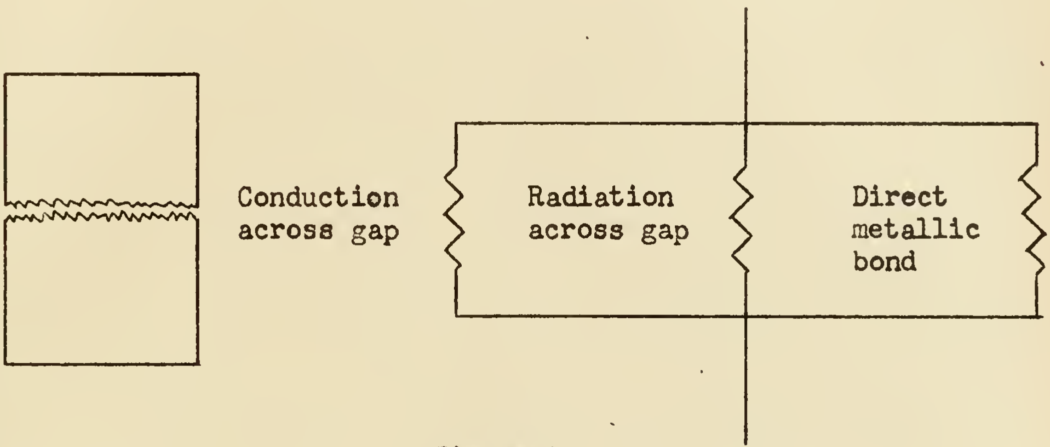


Figure 4

A survey of the literature indicates some introductory work in the field. Jacobs and Starr (1) investigated the thermal conductance of interface joints between gold, silver, and copper in a vacuum as a function of pressure at room temperature and at the temperature of boiling nitrogen. Brunot and Buckland (2) determined the thermal resistance of joints at the interface of laminated and cold-rolled steel under various contact pressures and surface roughnesses. The thermal resistance of low-carbon steel joints was measured by

Kouwenhoven and Potter (3) at two temperature levels for various pressures and surface roughnesses. The temperature drop across the interface was not a parameter in these tests. Weills and Ryder (4) present measurements of thermal resistance for dry and oil-filled joints of various materials as a function of pressure, surface finish, and temperature. Heat flow and temperature drop were partially investigated as parameters.

The work by Barzelay, Tong, and Holloway (6,7) is the most comprehensive to date. Their approach is a departure from the above in that the objective was to determine the effect of most of the pertinent parameters on the thermal conductance across the interface of structural joints using aircraft structural materials. The parameters included were heat flow, temperature drop, temperature level, surface condition, and pressure. It is noted, however, that the effect of different included media was not a part of their work. J. D. Keller (5) states in part,

> It would have been of great interest if at least some of the author's tests could have been repeated with the contacts in a vacuum, and again, with the gaps between the surfaces filled with a gas of much higher thermal conductivity than air, such as hydrogen or helium.

The absense of experimental data in the literature on the effect of included media, together with Mr. Keller's statement of interest in the problem prompted the author to do experimental work in this field as a thesis topic.

The objective of this thesis is to investigate the effect on the thermal conductance of including vacuum, air, and helium within the interface formed by two solid surfaces in simple mechanical contact.

It was immediately noted that the effect of the other parameters associated with the problem have been investigated in some detail, particularly by Barzelay, Tong, and Holloway (6,7). For this reason plus that of time and equipment limitations, it was decided to maintain as constants as many parameters as possible in order to obtain at least one set of data involving air, vacuum, and helium as the included media. With this end in mind, the equipment was designed and test schedule carried out accordingly.

CHAPTER II

DESCRIPTION OF THE APPARATUS

1. General description.

Two general views of the test installation are shown in figures 9 and 10. The apparatus used can be divided into the following groups:

a. A heat source to furnish the heat input.

b. A heating head at high temperature to serve as a heat reservoir.

c. A pair of specimens to provide the interface to be studied.

d. A sealing gasket to contain the included media within the interface gap.

e. A cooling head at low temperature.

f. A heat sink or coolant to maintain the cooling head at low temperature.

g. Thermal insulation.

h. Compressive loading machine.

i. Temperature sensing, indicating, and recording devices.

j. Various media.

2. Detailed descriptions.

a. Heat Source: Two CHROMOLOX cartridge element heaters model number C-503C, manufactured by the E. L. Wiegand Co. and rated at 250 watts each were the heat source. They were controlled manually as to heat output by means of a General Radio Co. VARIAC and Weston Electrical Instrument Co. ammeters and voltmeters.

b. Heating head: The heating head assembly is shown in figure 11. It consists of a heavy stepped cylinder machined from a four inch bar of solid copper. The heater elements were inserted in the heating head as indicated and secured there by means of two small stainless steel retaining strips. The lower end of the heating head was recessed 0.040 inch to allow more vertical stability of the entire test assembly. Copper was chosen as the material for the heating head because of its excellent thermal properties and also because of the fact that when compressive load was applied to the test assembly, the soft copper heating head would deform as necessary to insure uniaxial application of the load to the test specimens.

c. Test specimens: The test specimens which were used to provide the interface for testing were machined from a single bar of 61-S aluminum alloy, A.S.T.M. number B211-46T, alloy GS 21 (bar stock). A drawing of the test specimens appears as figure 12. The specimens were prepared by conventional means and then the interface surface was burnished with a blunt carbide tool to provide a surface roughness of the order of thirty microinches average roughness as determined by means of a General Electric Co. surface comparator. A profile was then taken of the interface surface using a surface analyzer manufactured by the Brush Development Co. This profile revealed that the average surface roughness was thirty-five microinches and that the height of the highest peaks and valleys present was eighty microinches. The average flatness of the test surfaces was found to be 0.0002 inch. The two ends of the test specimens were checked parallel within 0.0002 inch. The latter two operations were carried out by comparison with a standard surface plate.

The specimens were next scribed to an accuracy of 0.01 inch for proper location of the holes to be drilled to receive the thermocouples which were used to determine temperatures in the test specimens. Thermocouple wires of Brown and Sharpe gage 30 copper-constantan were used and the necessary holes were drilled using a number 50 drill (0.0700inch diameter) with kerosene as a lubricant. Two thermocouples at the same level on the test specimens were inserted at two different depths into the specimens in order to determine radial temperature variations, if any. The schedule of thermocouple locations is outlined in figure 8.

The Brown and Sharpe gage 30 copper-constantan thermocouple wire was chosen because of its availability and because it was the smallest wire practicable with which to work in this temperature range. The use of smaller wire tended to minimize the instrumentation error. After the wire ends were stripped of their fibreglass insulation, the thermocouple bead was formed by welding the wire ends together using an arc drawn with a special mercury pot. The length of the thermocouple which was to lie within the specimen was dipped in Glyptol lacquer to provide protection and insulation. Each thermocouple was then inserted in its hole which had been filled with wet copper dental cement after the method developed by Dr. H. D. Baker outlined in reference (4). The copper cement dried rapidly and served as an excellent heat conductor and held the thermocouples securely in their holes. On test, the thermocouple wire broke at the surface of the specimen before the dental cement released its hold within the hole.

d. Sealing gasket: The major problem in introducing a medium other than air between the interface of the test specimens was that of sealing the interface. This could have been accomplished, in general, by two means. One would have been to "can" the entire test assembly; the other would be to seal only the joint between the test specimens. The "canning" method was discarded because of the difficulty in sealing stuffing tubes on approximately twenty small insulated wires that would have to run to the test assembly. The gasket method introduced the problem of what material could withstand temperatures of up to 300°F. and still retain enough plasticity to be a satisfactory seal for the interface joint. It was decided to machine the gasket from molded TEFLON.

TEFLON or polytetrafluoroethylene is a relatively new and very versatile plastic material manufactured by the E. I. DuPont de Nemours Co., Inc. It consists of a fine white powder which can be made into solid shapes by compressing in molds and sintering at a temperature in excess of 600°F. When in solid form, Teflon exhibits good dimensional stability over a temperature range of -450°F. to +500°F., softening at 525°F. It is an excellent thermal and electrical insulator.

A solid cylinder of Teflon four and one-half inches in diameter and six inches long was obtained and the sealing gasket was machined from it, using techniques similar to those for machining aluminum. The first gasket machined had to be discarded after it was discovered that Teflon loses some of its dimensional stability when cut to thin sections. Thus the first gasket attempted was found to be too loose

when fitted on the test specimens. The second gasket was machined 0.010 inch undersize and proved to be satisfactory.

The gasket material was drilled and tapped to receive a 3/16 inch stainless steel nipple through which the various media were introduced. An adjustable stainless steel banding clamp was fitted over the Teflon gasket after it was in place on the test specimens in order to hold it more securely in place and to better enable it to hold its pressure and/or vacuum after thermal expansion.

A sketch of the sealing gasket appears as figure 13.

e. Cooling head: The cooling head was machined from a solid bar of copper and consists of a cylinder with a central axial hole and a number of smaller radial holes as shown in figure 14. The cooling water was admitted into the central hole and flowed upward and outward through the radial holes so as to carry away the heat. Copper was chosen as the material for the cooling head because of its excellent thermal properties and because it tended to undergo slight plastic deformation to permit the application of a uniaxial compressive load. The top of the cooling head was recessed 0.040 inch to provide more vertical and lateral stability for the test assembly.

f. Heat sink: Tap water was used as the coolant sprayed from the cooling head. A manually operated regulating valve provided the necessary control. It was found that the capacity of the cooling head was such that minor fluctuations in the water flow did not affect the experimental data measureably. A drip pan made of 20 gage galvanized iron collected the spray and returned it to the building drain system by way of a flexible hose connection.

g. Thermal Insulation: Except for a small portion of the heating head and the water spray section of the cooling head, the entire assembly was insulated in a one inch thick shell of molded magnesite. The insulating shell was molded from a piece of three inch steam pipe lagging leaving several small openings for wires, hose, etc. At no time during the experimental work did the temperature of the exterior of the insulation exceed 110°F. The self-aligning head of the compressive loading machine was insulated from the heating head of the test assembly with a one and one-half inch thick block of molded asbestos.

h. Compressive loading machine: The compressive load on the specimens was applied by placing the test assembly in an American Machine and Metals Co. RIEHLE testing machine. By using the six thousand pound scale the necessary accuracy was obtained. The load was applied through a ball and socket type loading plate supplied with the machine to further insure an equally distributed load on the test specimens.

Some difficulty was experienced with the Riehle testing machine in keeping a constant load while undergoing a thermal transient. Such transient conditions necessitated continual adjustment of the loading screw position until steady state conditions were reached. This difficulty could have been avoided if a constant load device had been available for the Riehle testing machine or if a dead-weight loading stand were available in this department.

i. Temperature devices: The sixteen copper-constantan thermocouples imbedded in the test specimens were run to a terminal board at the front of the testing machine. From the terminal board, the thermocouples

were connected in such a manner that they could be read and recorded in several ways:

1. The thermocouple readings could be read absolutely referenced to an ice junction on a Rubicon portable precision potentiometer.

2. Each geometrically opposed pair of thermocouples in the upper and lower specimens could be read referenced to the cooler of the two. By differentially connecting the thermocouples in this manner, more accurate determination of the temperature difference across the interface could be accomplished with a minimum of additional instrumentation.

3. Six thermocouples from the A, B, and C rows of the upper and lower specimens were referenced to the ice junction and were connected to a Leeds and Northrup Co. SPEEDOMAX six channel potential recorder. In this manner it was easy to observe temperature conditions along the test assembly and determine when steady state conditions had been reached.

Schematic circuit diagrams appear as figures 15, 16, and 17.

j. Various Media: The three media whose influence was to be investigated were vacuum, air, and helium representing low, average, and high thermal conductivity media. Vacuum was applied to the test interface by means of a W. M. Welch Mfg. Co. DUO-SEAL vacuum pump connected by natural rubber hose to the nipple in the joint sealing gasket. The air source was atmospheric from the ambient air in the room. The helium was U. S. Navy grade A helium supplied in standard size bottles and reduced to an approximate pressure of one and one-half inches of mercury through a Victor Equipment Co. reducing valve.

CHAPTER III

EXPERIMENTAL PROCEDURE

The equipment was assembled as shown in figures 9 and 10. All interface junctions on the test specimens were thoroughly cleaned with acetone. The interfaces on the heating and cooling heads were scoured with very fine steel wool and cleaned thoroughly with acetone. The test assembly was then compressed to the maximum anticipated load as a preliminary treatment designed to smooth out unusual high spots on the surfaces which would produce an abnormally high resistance. This treatment did not, in reality, produce any noticeable change in the surface roughness as shown by the Brush surface analyzer. It is very probable that, had there been any abnormally high spots present, this treatment would have improved the situation. The geometric probability of choosing such a spot for check by the surface analyzer was very slight.

The test apparatus was next operated at the maximum anticipated load and the heaters were slowly brought up to rated output. This step was designed to familiarize the author with the behavior of the apparatus, test the temperature sensing and recording apparatus, and to observe maximum practical limits of operation. As a result of this test, several "bugs" were worked out of the Speedomax temperature recorder and the thermal insulation before the actual tests were started.

By the very nature of the problem, the test schedule was immediately broken down into three series of tests, namely, with air, vacuum, and helium as the medium between the interface. The rated output of the

heaters permitted an upper limit of approximately 250°F. as the mean temperature so it was decided to make runs at 150°F., 200°F., and 250°F. In order to study the influence of one more parameter and to present data for the more comprehensive problem, the pressure was also varied to give runs at 100, 200, and 300 pounds per square inch.

All other known parameters involved were kept as near constant as possible so as not to overcomplicate the interpretation of the experimental data. The cooling water flow rate was held constant during all runs. During the vacuum runs, the vacuum was held as near thirty inches of mercury as possible. During the helium runs, the helium pressure was maintained at 1.4 inches of mercury to insure a positive helium supply to allow for leakage from the sealing gasket but not so high as to introduce a density problem.

With this planned series of tests in mind, the experimental test schedule was carried out in the following sequence:

A. Air Series

1. $T_m = 150°F.$; $P = 200, 300, 100$ p.s.i. in that order.
2. Repeat A1 with $T_m = 200°F.$
3. Repeat A1 with $T_m = 250°F.$

B. Vacuum Series

1. Repeat A1, A2, and A3 with vacuum as the interface medium.

C. Helium Series

1. Repeat A1, A2, and A3 with helium as the interface medium.

Readings were taken only after absolutely steady state conditions had been attained. The time required to attain steady state from a cold start was approximately four hours. The time necessary to again reach

steady state after a relatively small change of temperature level or pressure was two hours. The average time to complete a run was eight hours. At the end of each run consisting of three sets of readings taken at three pressures with constant medium and constant mean temperature, the test assembly was disassembled, the interfaces recleaned with acetone and the test assembly reassembled. This procedure was followed for several reasons. First, it insured that no foreign matter including scale, water droplets, or dust had become introduced. Second, it assured a reorientation of the specimens upon reassembly.

The use of a joint sealing gasket in lieu of "canning" the entire test assembly afforded a means of insuring that the medium being introduced, was, in actuality, the medium present between the peaks and valleys of the faces of the test specimens. This was accomplished by using a planned sequence of operations. Upon reassembly of the test apparatus, the test specimens were separated at the interface by hand a distance of at least one-eighth of an inch. The adjustable clamp on the teflon sealing gasket was tightened to hold the specimens apart the desired amount. For the air runs, the compressive load was applied at this time; air being already the entrapped medium. For the vacuum runs, the thirty inch vacuum was applied for a period of from one to two hours with the interfaces thus separated before applying the compressive load. For the helium runs, a vacuum was applied several times in a cyclic manner, relieving the vacuum with helium. Following this, helium pressure was applied for a period of three to four hours at a pressure of eight inches of mercury to insure positive helium leakage from the joint sealing gasket. With the interfaces thus separated and

with helium positively leaking out from the gasket, the compressive load was then applied and the helium pressure reduced to the value of 1.4 inches of mercury. The Teflon sealing gasket has a waxy consistency and readily permitted the test specimens to move the one-eighth inch separation without losing its sealing qualities.

CHAPTER IV

PRECISION OF DATA

It is virtually impossible to estimate for any given reading the exact amount that the recorded data deviated from the actual conditions existing in the test assembly. The temperature sensing, detecting, and recording instrumentation was such that there were many potential sources of error that could be additive or subtractive in varying amounts for any given set of data. Every effort was made to keep the sources of error down to a minimum and in addition, efforts were made to keep the magnitude of the errors down to a minimum. It is appropriate to discuss several of the major sources of error in some detail.

The most important source of error was in the determination of the temperature gradients and the temperature differences actually existing at the interface of the test specimens. From these values the numerical values of thermal conductance were obtained. Therefore, any errors existing in the thermocouple circuit are directly reflected in the experimental results obtained. While these readings of temperature gradient and temperature difference were computed by use of a plot of temperature vs. distance, the absolute errors in individual readings were of little consequence so long as they were uniform in all thermocouples. The thermocouples in the test specimens were of the same length and made of wire from the same lot and read in the same sequence on the same potentiometer. A typical temperature vs. distance curve appears as follows:

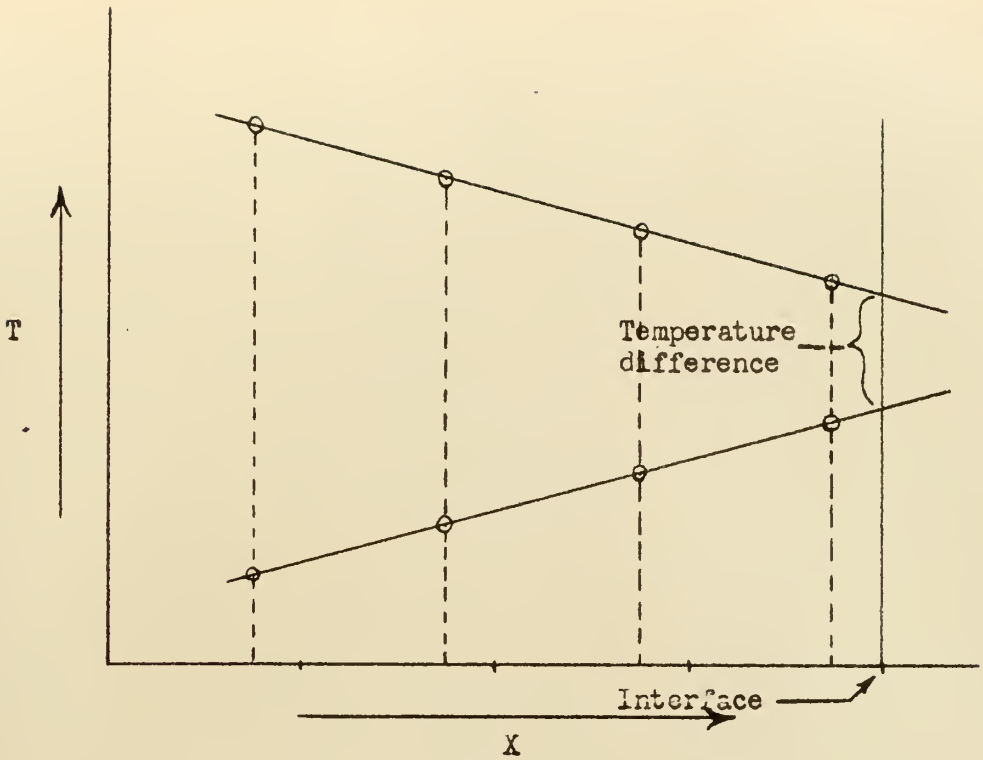


Figure 5

It appears that, in the determination of the interface temperature difference, the maximum error originating from thermocouples, potentiometer, and extrapolation of the curve is of the order of $\pm 1^{\circ}$F. This immediately introduces the possibility that the computed results may be inaccurate by as much as $\pm 20\%$ or more in a run having a temperature difference in the order of 5°F. However, it must be remembered that the 20% error figure is a maximum, and any one set of data will have gone through several averaging processes before appearing as an absolute value. Therefore any extremes either in the plus or minus direction will tend to become averaged out before appearing as the final curves of

conductance vs. the variable parameters.

Precise measurement of the axial location of thermocouple beads was necessary for an accurate determination of temperature gradient. For this reason the locations were marked after measuring on a surface plate using a vee block support for the specimens. The drilling of the holes was done with the specimens also supported in this manner. It is estimated that the locations of the thermocouples are correct within 0.01 inch, which is within the maximum accuracy of plotting.

A third source of error was in non-parallel heat flow. This phenomenon could be caused by (a) loss of heat through the insulation and (b) non-uniformities in the heat path. The insulation used proved to be adequate for keeping the heat loss to the surrounding atmosphere to a minimum. No measurements of heat loss were made but it suffices to say that the insulation was only slightly warm to the touch when operating the heaters at rated capacity. Non-uniformities in the heat path were kept to a minimum by filling the thermocouple holes with copper dental cement. These sources of error proved to be inconsequential as shown by the fact that the maximum variation of temperature on one level was less than five degrees Fahrenheit. Wherever there was a variation of absolute temperature in this manner, the plot of differential temperature vs. distance revealed the true value.

For all experimental runs, the absolute temperatures and differential temperatures were plotted against distance. The absolute temperature curves were used to determine temperature gradients, mean temperatures, and an estimate of temperature difference at the interface. The differential temperature curves were used to determine the value

of temperature difference at the interface. Greater accuracy in the determination of all quantities was obtained in this manner.

CHAPTER V

EXPERIMENTAL RESULTS

It was at first decided that the true test of the construction of the test apparatus would be to reproduce some of the results of previous experimental work in the field. This necessitated selecting an air run as all previous work of this nature has been with air as the included medium. It also necessitated selecting data whose mean temperatures and compressive loads were within the same limits as those of the author. For comparison purposes, data was selected from the results of Barzelay, Tong, and Holloway (7) and compared with that of the author. The only correction factor applied for comparison purposes is that to account for the difference in thermal conductivity of the material used for the test specimens.

	Thermal conductance coefficient, h			
	@200°F.		@250°F.	
	uncorr.	corr.	uncorr.	corr.
From ref. (7) @ 90 psi	1350	1900	1450	2040
From the author @ 100psi	----	1815	----	1920
Variation from ref. (7)	----	4.8%	----	6.2%

Table 1

It may be seen that if a correction were applied for surface roughness, pressure, and/or other variable parameters, it may be presumed the data would be even more in agreement. Nevertheless, Table 1 clearly shows that the order of magnitude of the data is in agreement with data previously obtained by other workers in the field.

The apparatus was also checked for repeatibility to insure that under a given set of conditions, the recorded and computed values from one run to another, would agree. This phase was conducted for air as the included medium and at several pressures and mean temperatures. The test assembly proved itself able to reasonably repeat data under similar conditions. The results follow:

Run	T_m	P	h	Percent variation from ave.
2	142	200	2150	nil
40	148	200	2140	nil
3	142	300	2560	-4.5%
41	145	300	2790	+4.5%
4	143	100	1570	-4.5%
42	151	100	1710	+4.5%
5	197	200	2360	+2.0%
6	202	200	2280	-2.0%
9	238	200	2535	+3.5%
10	234	200	2360	-3.5%

Table 2

The equipment (and author) having demonstrated that they could indeed repeat previous data and reproduce the data of others with reasonable accuracy, the next steps were to conduct the experimental test procedure described in Chapter IV. A summary of all experimental data appears in Appendix I.

The families of curves representing the air, vacuum, and helium runs are plotted against mean temperature, figure 6, and pressure, figure 7. The average thermal conductance for each of the families of curves were computed; being limited to the small range of mean temperature and pressure over which data was recorded. These values of average thermal conductance are listed in table 3.

	Average thermal conductance (B.T.U./hr-ft^2-^{o}F.)		
	h computed by averaging data	h computed by area under curve	h mean average
Helium	5925	5900	5913
Air	2215	2195	2205
Vacuum	1405	1370	1388

Table 3

A study of the vacuum family of curves in figures 6 and 7 will reveal the following apparent conclusions:

a. In the virtual absence of a conducting medium, it is noted that nearly all of the heat is transferred by conduction through the metal and radiation across the gap. This fact may be borne out by examining the low pressure curves in figure 6. At low pressures, the thermal conductance shows only a slight rise with a large increase in mean temperature and temperature difference. The slight rise in thermal conductance may be attributed to a rise in radiation across the gap and conduction through the metal but does not approach the order of magnitude of increase to be expected if conduction through the medium was important.

b. As the pressure increases and the interface gap narrows allowing more metal surface to come into contact, radiation assumes a less important role. The end result is that at a pressure of 300 p.s.i., the conductance curve becomes exponential. Above 207°F. at 300 p.s.i., the conductance curve with vacuum crosses the 100 p.s.i. curve with air.

An analysis of the air family of curves in figure 6 reveals that the conductance varies in a manner that is essentially linear. This behavior is in accordance with the findings of Jacobs and Starr (1) and Weills and Ryder (4). However, a study of figure 7 will reveal that the air family of curves tends to approach a terminal value of thermal conductance in the vicinity of 3000 B.T.U./hr-ft^2-°F. at higher pressures. This latter behavior is similar to that noted by Kouwenhoven and Potter (3)

after work with smooth steel specimens. Thus it appears that the author's results with air as the included medium are a combination of the phenomena observed by previous workers in the field. Therefore these results neither prove or disprove the theories of linear behavior or terminal value of thermal conductance as advanced by the aforementioned workers. It still appears that the inconsistencies and insufficiency of the available data make it impossible to accurately predict the thermal conductance behavior with air as the included medium beyond the range of existing experimental data.

In contrast with the somewhat uncertain behavior of thermal conductance with air as the included medium, a study of the helium family of curves in figures 6 and 7 shows unquestionably that the conductance increases exponentially with both increased pressure and increased temperature level. This fact would indicate that both conduction and radiation across the helium gap are important mechanisms in the overall heat transfer process in addition to conduction through the metal. This is substantiated by the exponential rise in conductance at constant pressure with increasing temperature level and the exponential rise in conductance at constant temperature level with increasing pressure.

The mean values of the thermal conductance as shown in table 3, page 25, tend to show that there is no predominance of any single mode of heat transfer involved in the entire mechanism at the interface. If the value of 1388 B.T.U./hr-ft^2-$^\circ$F. were taken as a base value, applying a correction to account for the differences in conductivity of air as compared with helium as compared with zero conduction through the medium yields no results that can be correlated with values found

experimentally. If it were assumed that the radiation was zero at the lowest pressure-lowest temperature points, again there is no agreement when the ratio of conductivities of helium to air is applied. Thus it appears that the author substantiates the findings of Barzelay, Tong, and Holloway (6,7) that there is no evidence to support a contention that any one mode of heat transfer is predominant in the mechanism of heat transfer across an interface.

Regardless of the fact that no quantitative breakdown of the thermal conductance values into conduction through metal and/or medium and radiation across the gap is possible, the tabulated values of conductance in table 3 are of useful value. The relative magnitudes of conductance when a joint is formed between two metals in a medium of air, vacuum, or helium will give a worker in this field some indication of the results to be expected. For example, the heat transfer advantage to be gained across an interface formed in helium as compared with air is 5913/2205 or 2.68 times the conductance with air. Similarly, the insulating value of a vacuum compared with air between a smooth metal to metal surface is 1388/2205 or only .63 times the amount of heat transferred across a joint formed in air.

In summary, the following conclusions may be drawn:

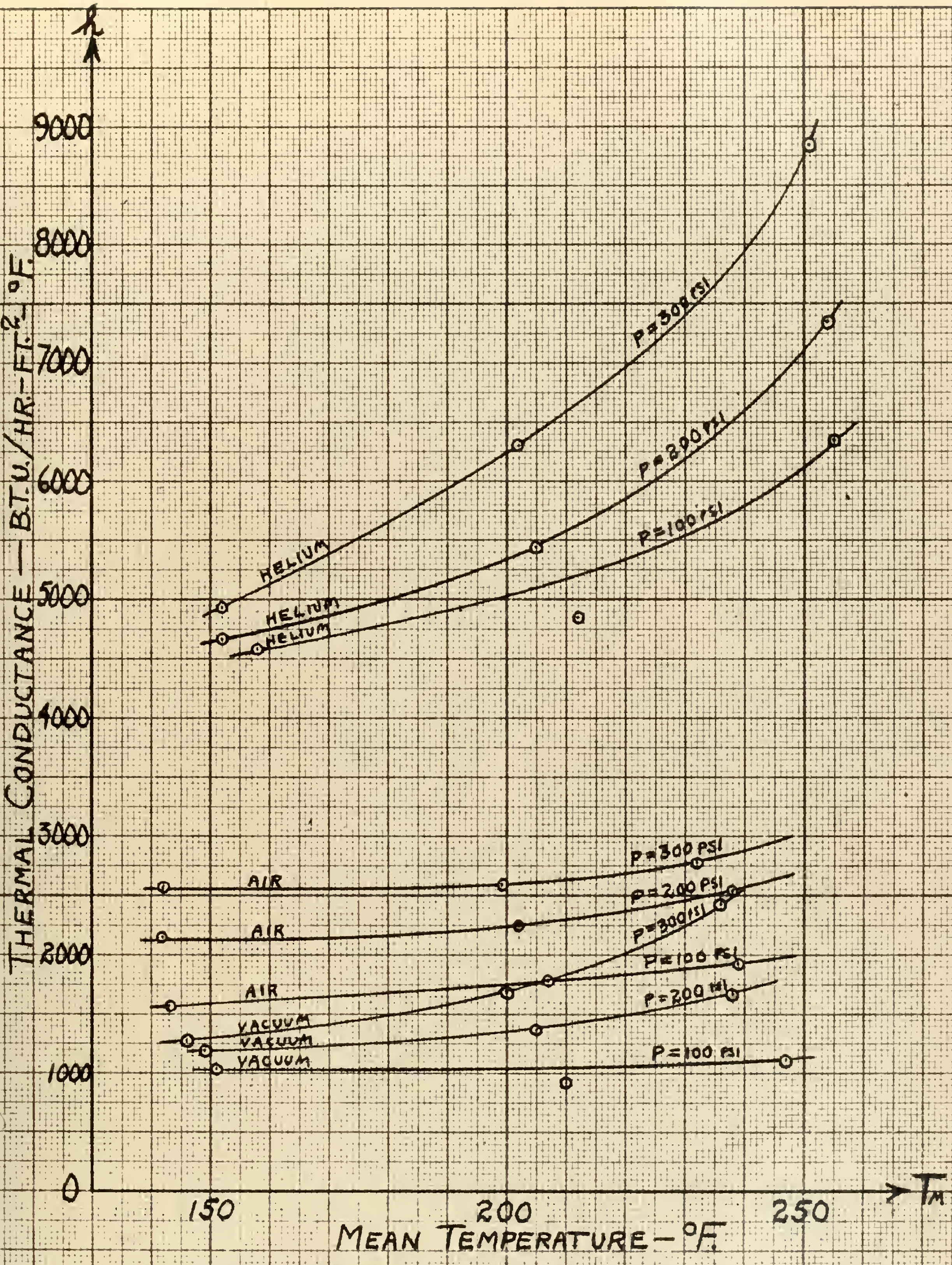
a. Heat is transferred across a smooth aluminum to aluminum joint between two solid cylinders pressed together with helium, air, and vacuum as the included media in the average ratio of 4.26--1.59--1.00 within the range of pressures and temperatures that were studied.

b. No single mode of heat transfer is predominant in the mechanism

of heat transfer across such a joint with a gas as the included medium.

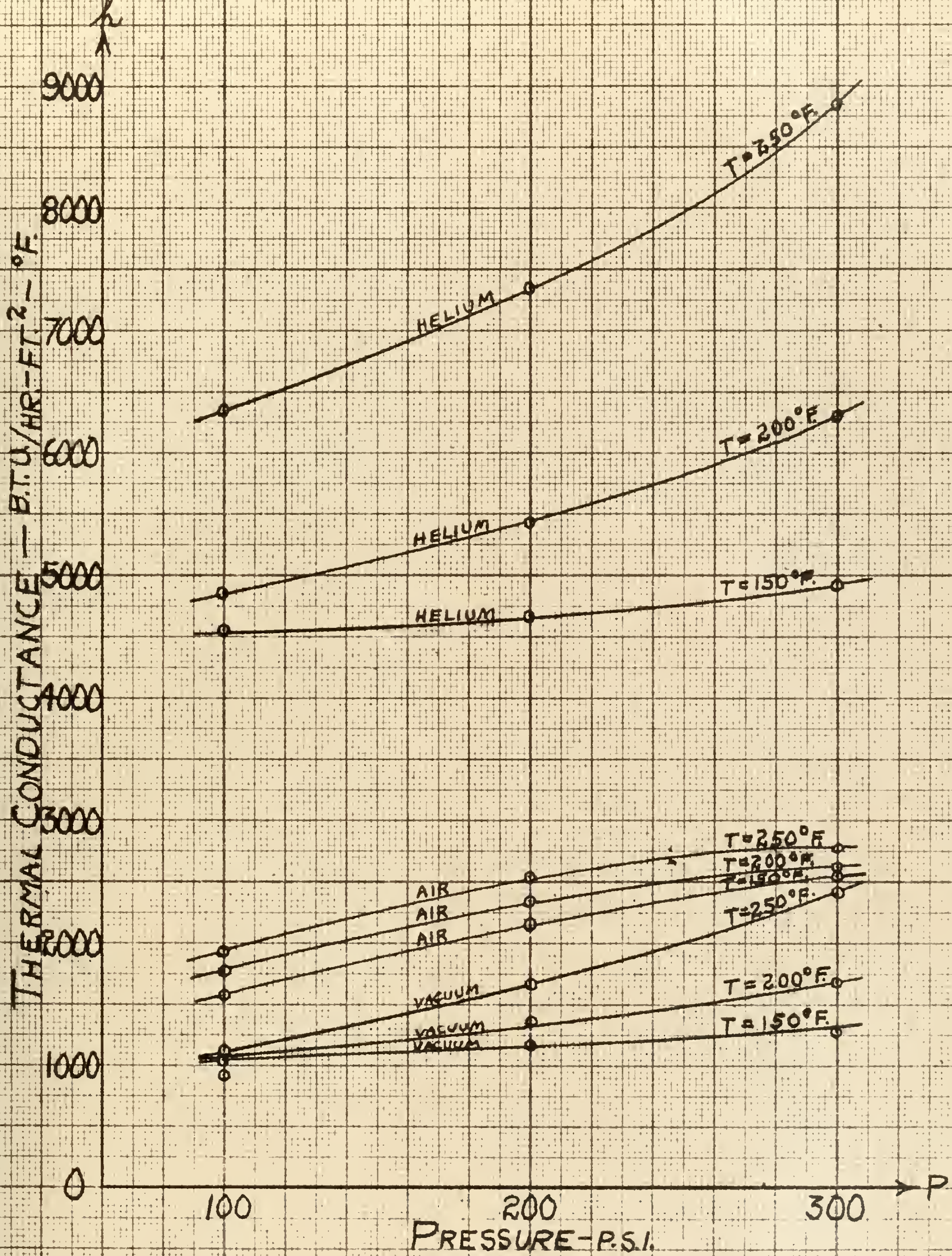
c. There is further need for more work in the field to extend the existing data over a wider range of applications and thus provide information for better understanding the mechanism of thermal contact resistance.

d. The resistance to the flow of heat between two solid surfaces in simple mechanical contact remains highly unpredictable.



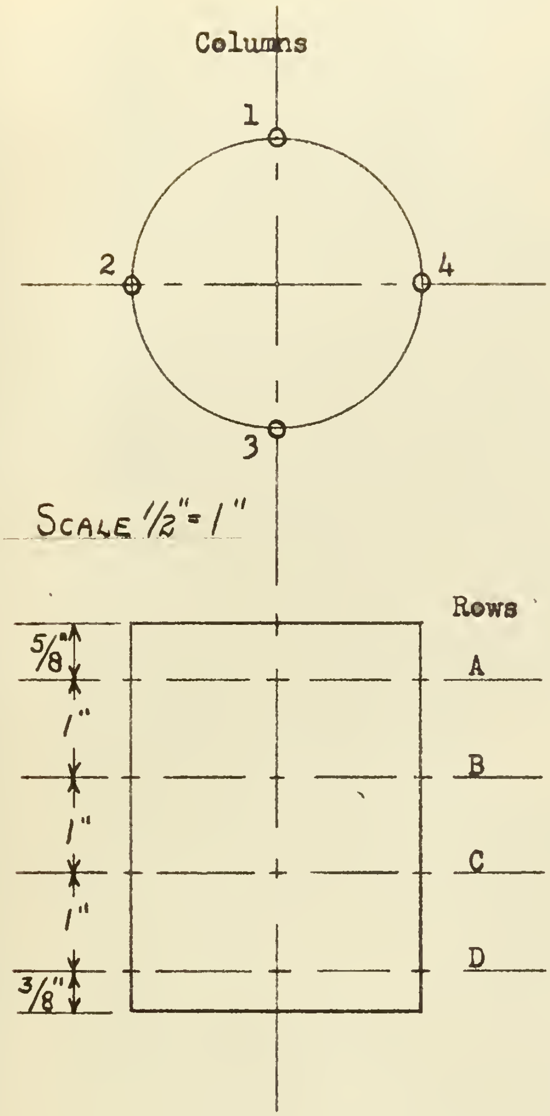
Graph: Thermal conductance vs. mean temperature

Figure 6



Graph: Thermal conductance vs. pressure

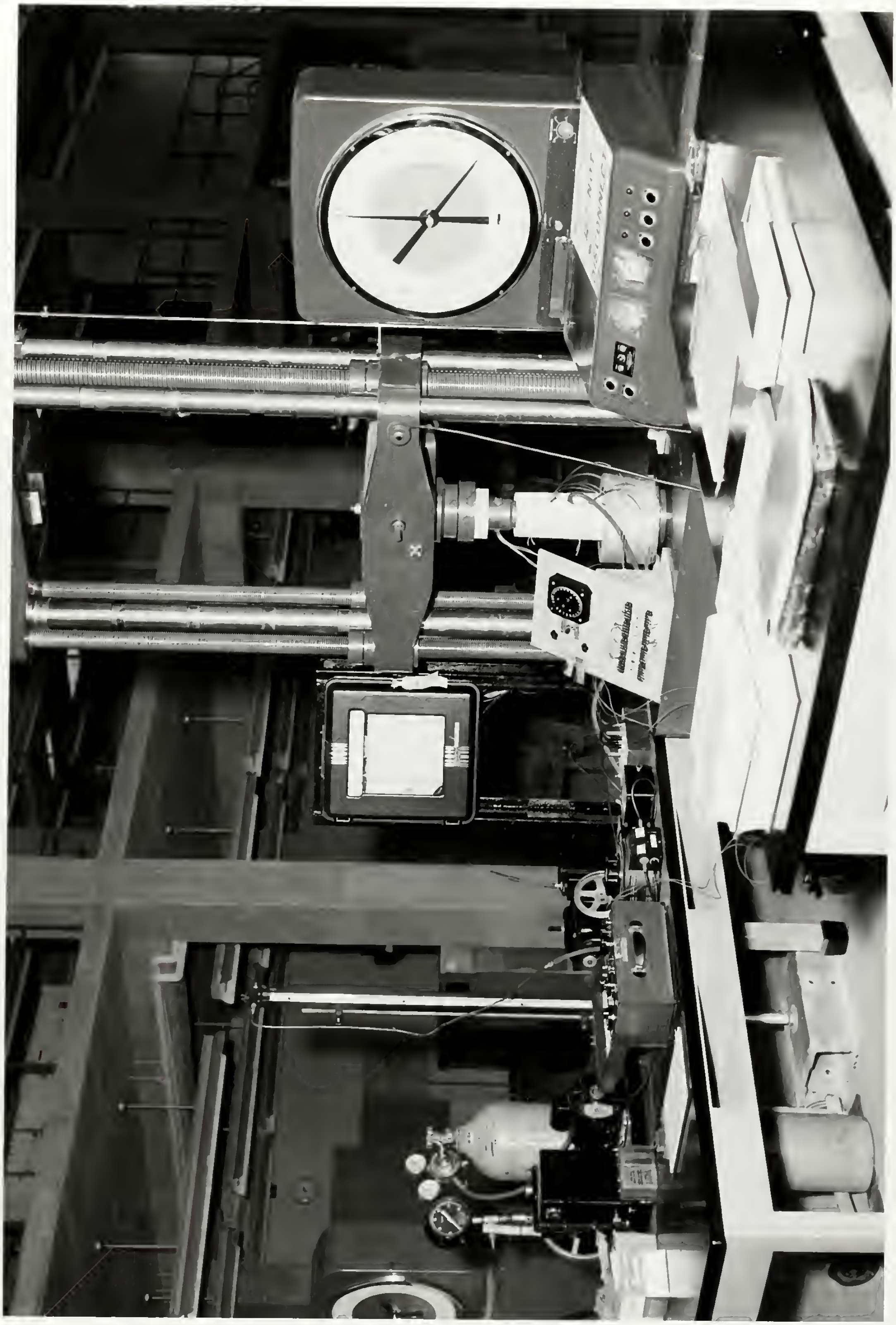
Figure V



Station	Depth
A1	3/4 in.
A2	none
A3	1 1/4 in.
A4	none
B1	none
B2	5/8 in.
B3	none
B4	1 in.
C1	1 1/4 in.
C2	none
C3	5/8 in.
C4	none
D1	none
D2	1 in.
D3	none
D4	3/4 in.

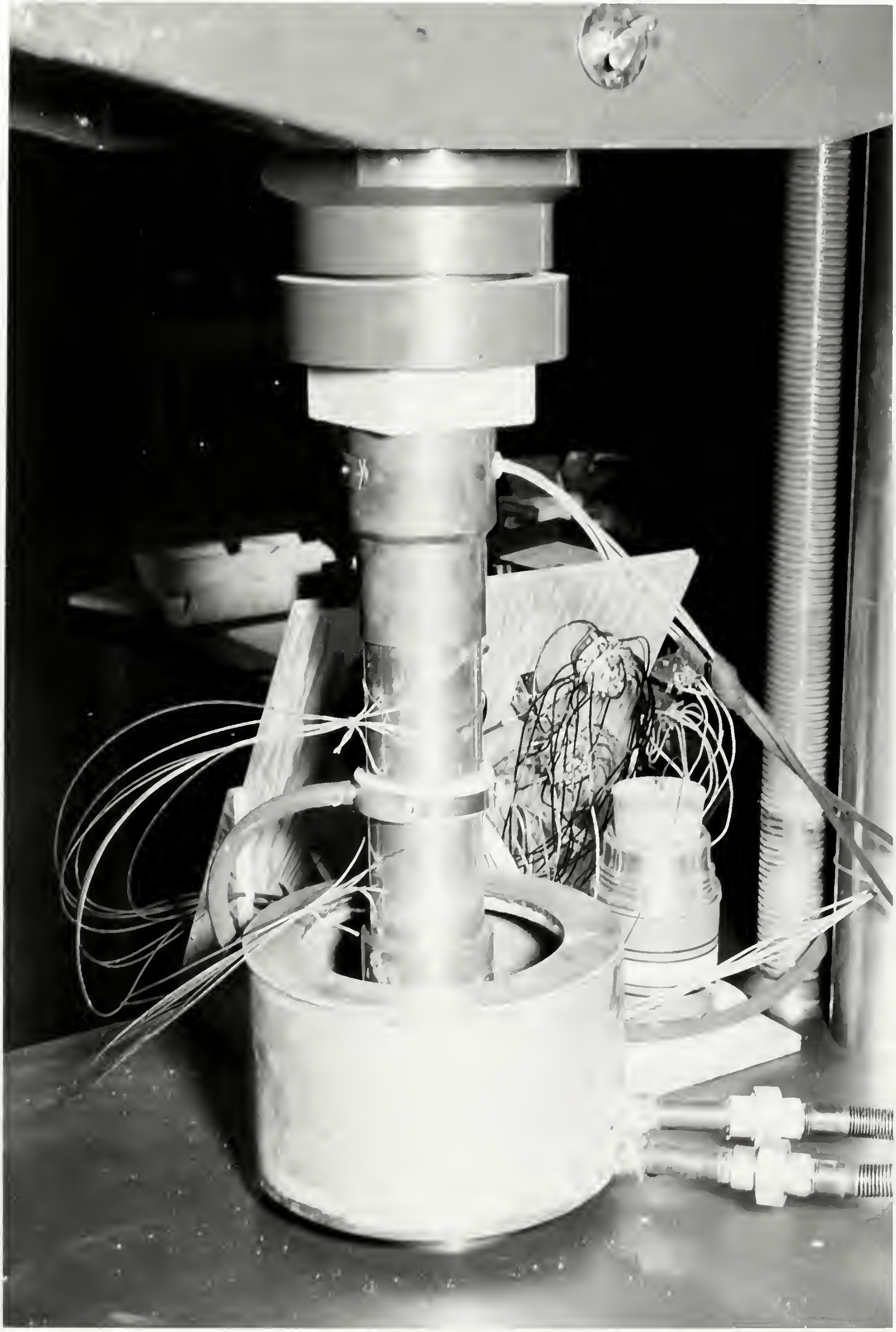
Schedule of thermocouple locations

Figure 8



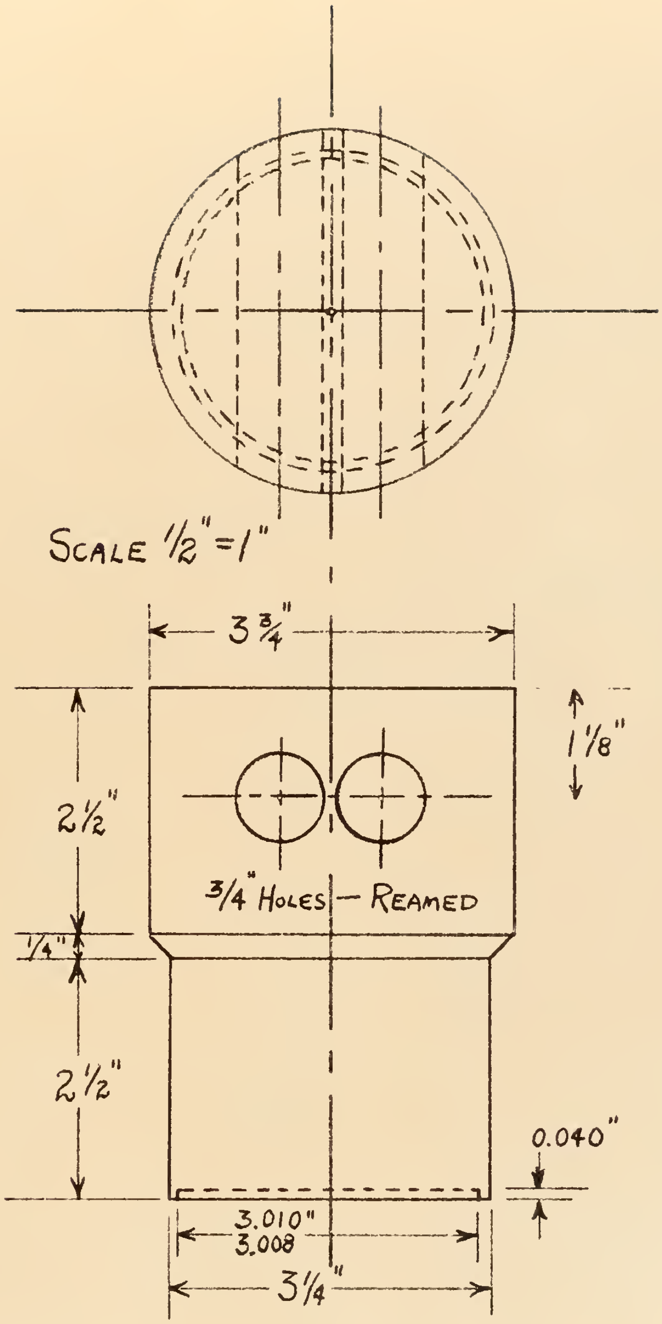
General view of test installation

Figure 9



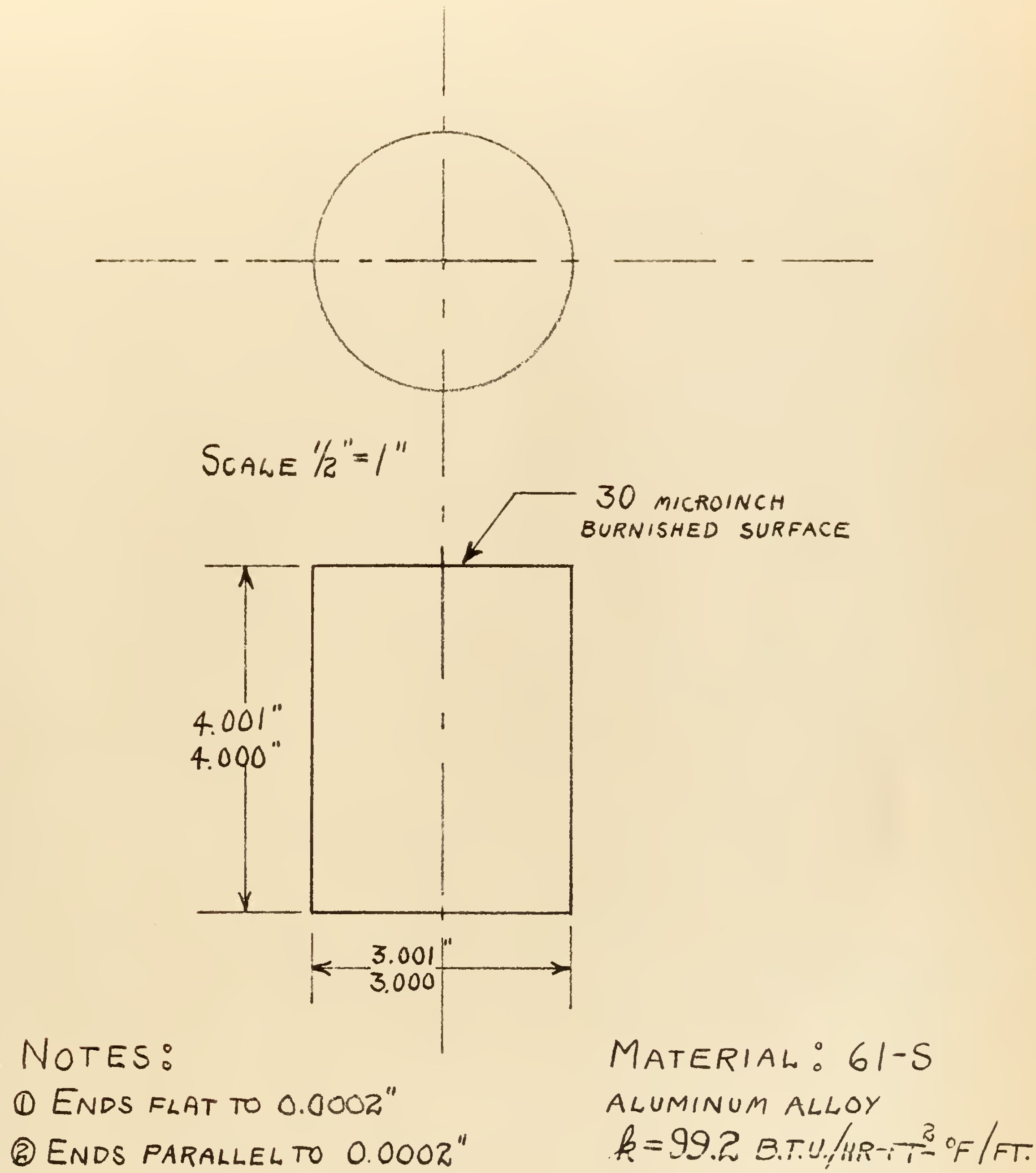
Close-up view of test assembly

Figure 10



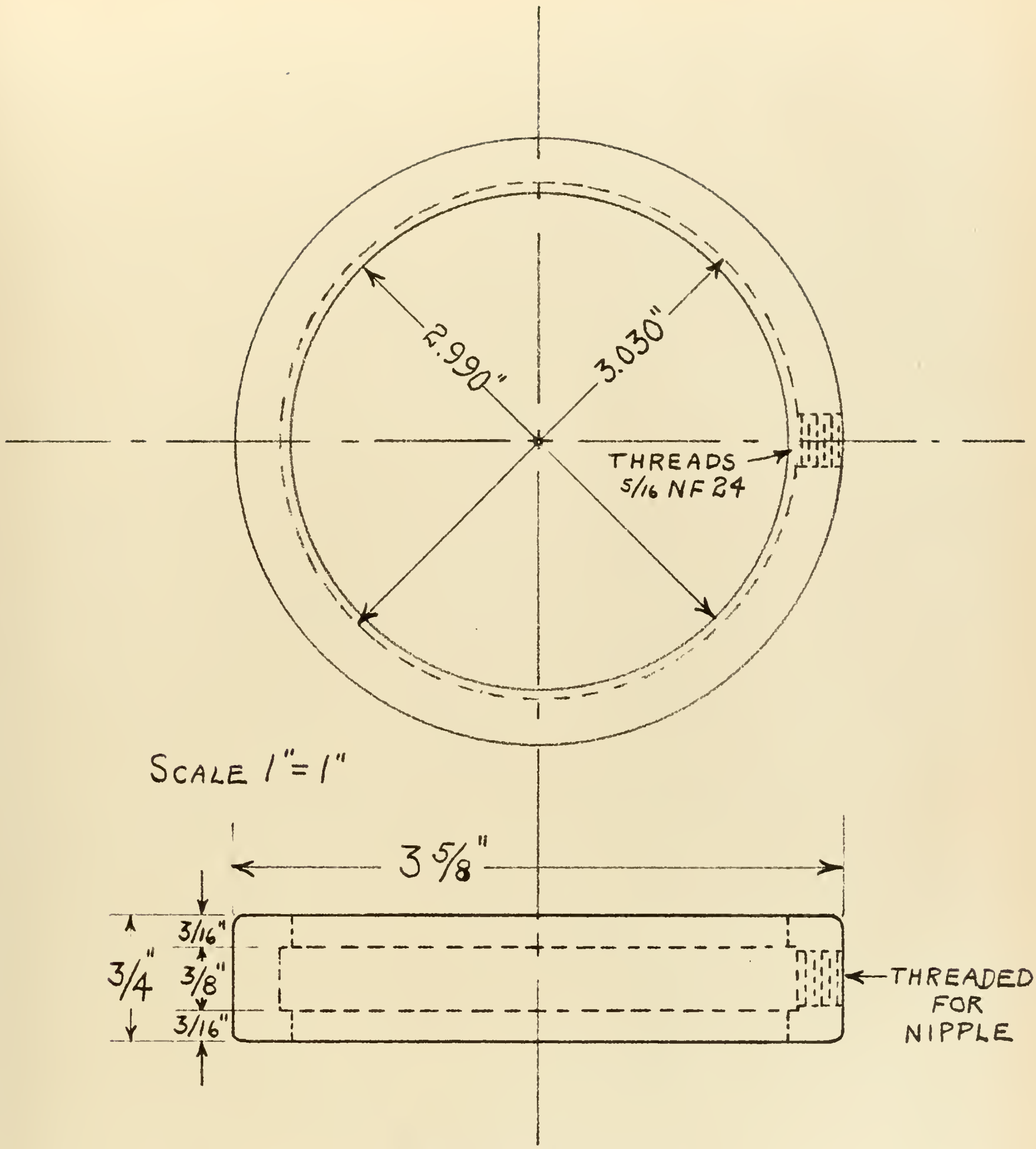
Heating head details

Figure 11



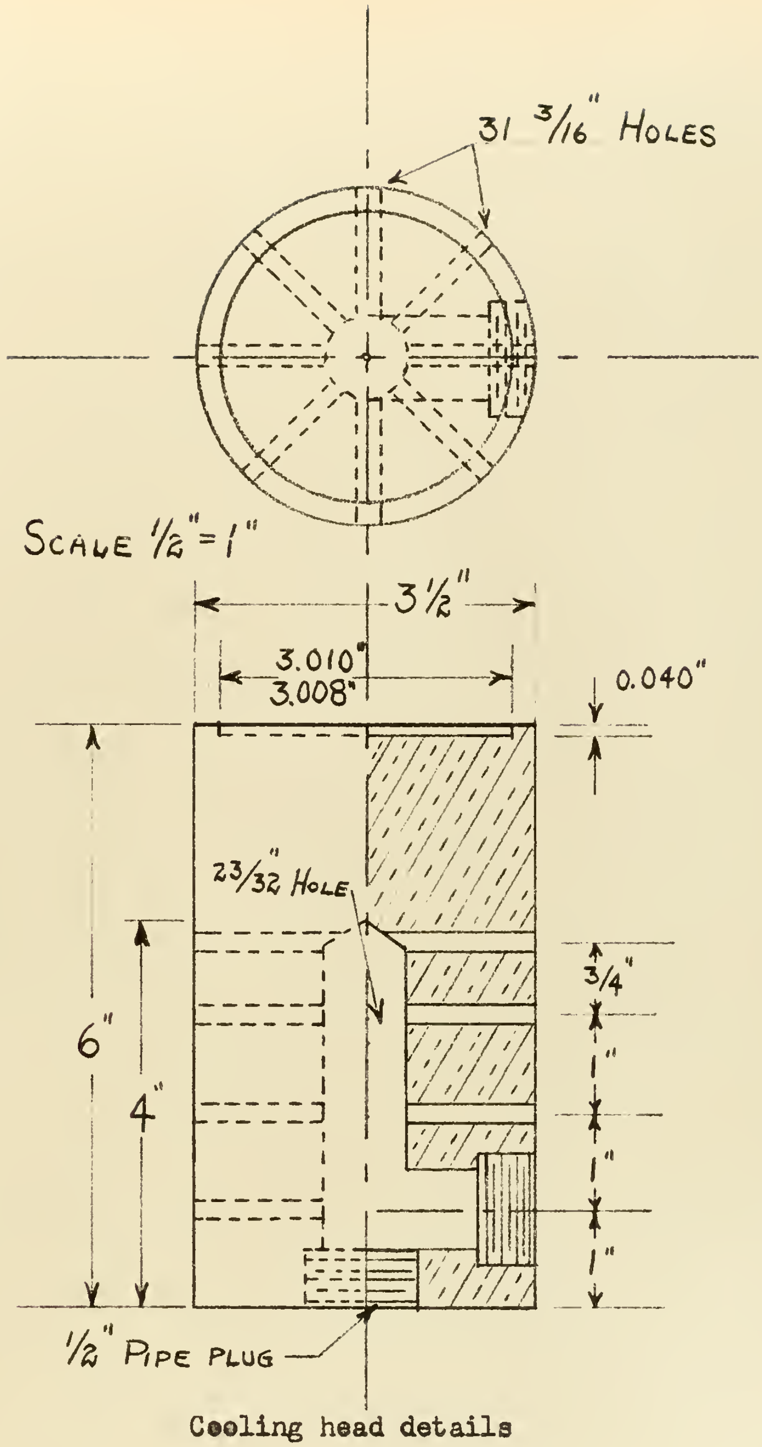
Test specimen details

Figure 12



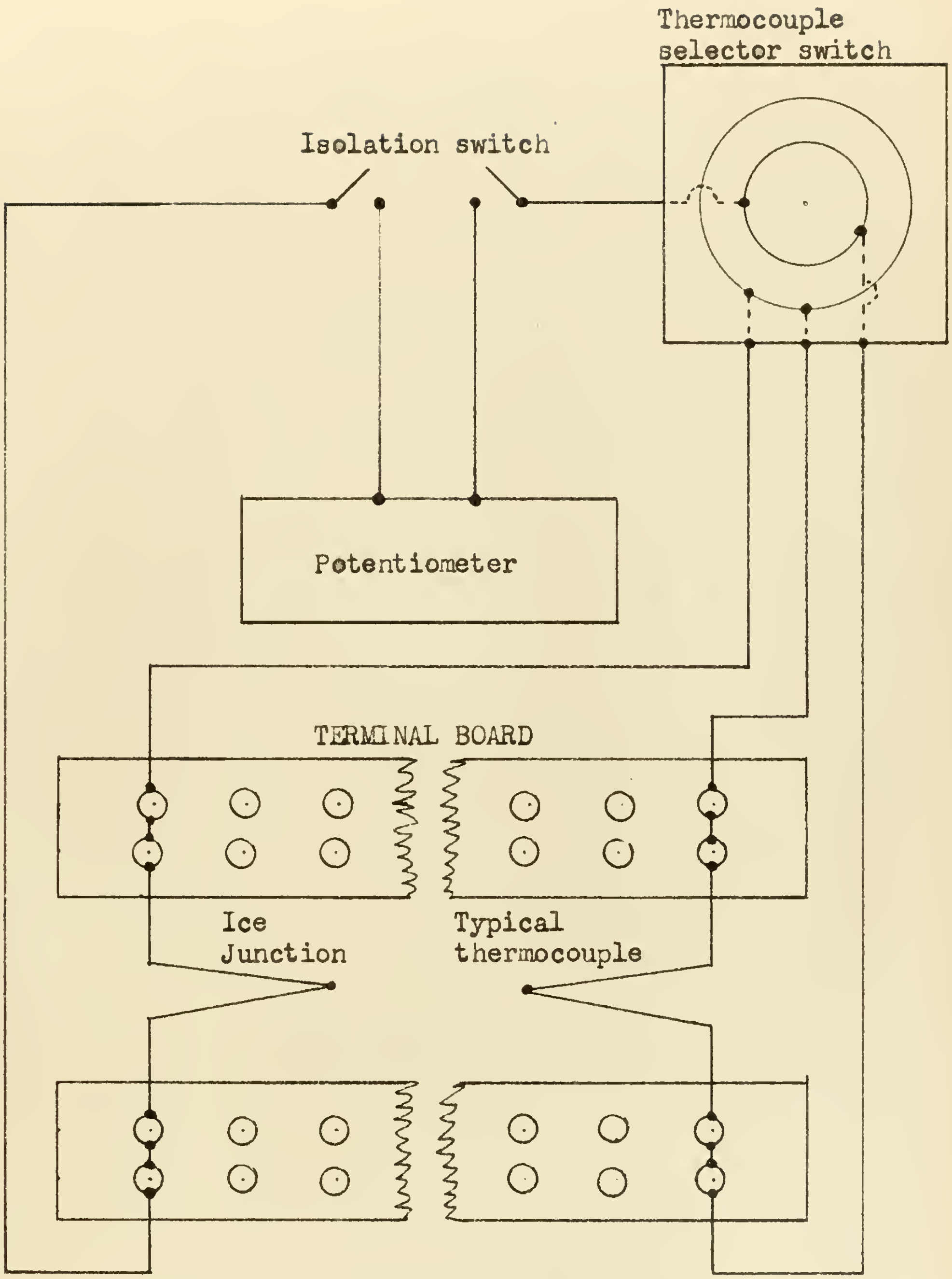
Sealing gasket details

Figure 13



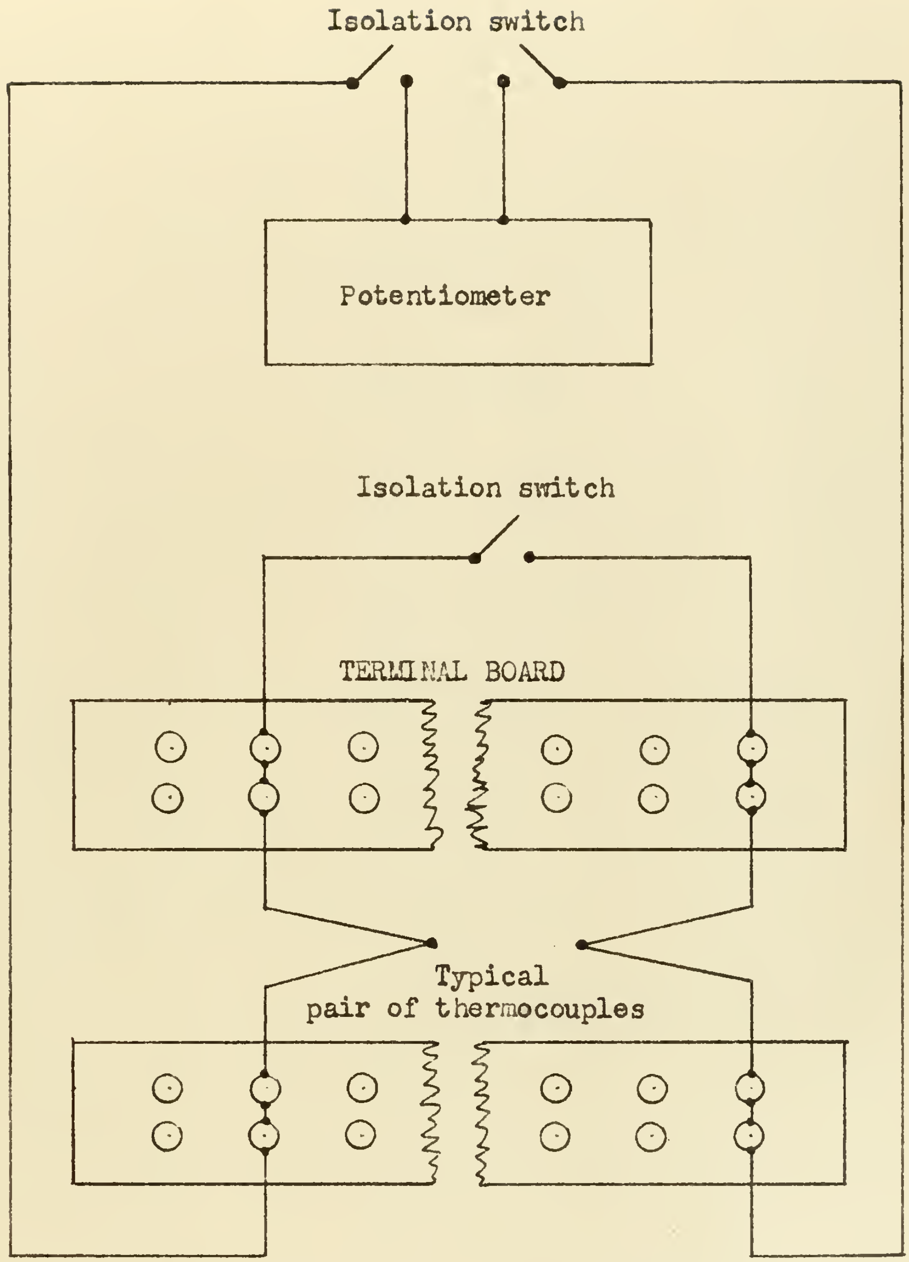
Cooling head details

Figure 14



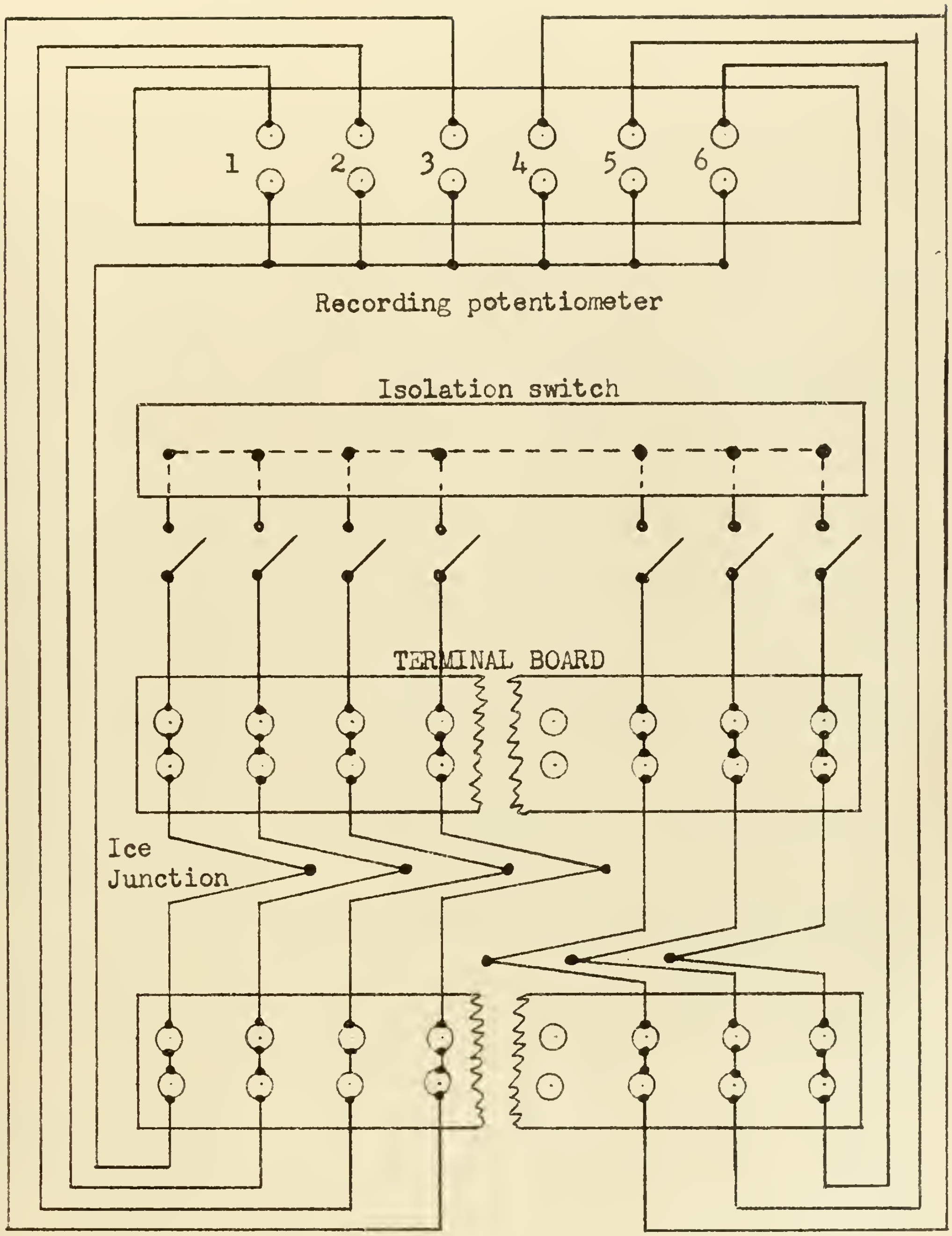
Thermocouple circuit (absolute)

Figure 15



Thermocouple circuit (differential)

Figure 16



Thermocouple circuit (recording)

Figure 17

BIBLIOGRAPHY

1. Jacobs, R. B. and Starr, C. — THERMAL CONDUCTANCE OF METALLIC CONTACTS Rev. Sci. Instr., Vol. 10, April 1939, pp 140-141

2. Brunot, A. W. and Buckland, F. F. — THERMAL CONTACT RESISTANCE OF LAMINATED AND MACHINED JOINTS, Trans. A.S.M.E., Vol. 71, No. 3, April 1949, pp 253-256

3. Kouwenhoven, W. B. and Potter, J. H. — THERMAL RESISTANCE OF METAL CONTACTS The Welding Journal, Vol. 27, No. 10, October 1948, pp 515s-520s

4. Weills, N. D. and Ryder, E. A. — THERMAL RESISTANCE MEASUREMENTS OF JOINTS FORMED BETWEEN STATIONARY METAL SURFACES Trans. A.S.M.E., Vol. 71, No. 3, April 1949, pp 259-266

5. Keller, J. D. — DISCUSSION OF REF. (4), pp 266-267

6. Barzelay, M. E., Tong, Kin Nee, and Holloway, G. F. — THERMAL CONDUCTANCE OF CONTACTS IN AIRCRAFT JOINTS, N.A.C.A. TN 3167, March 1954

7. Barzelay, M. E., Tong, Kin Nee, and Holloway, G. F. — EFFECT OF PRESSURE ON THERMAL CONDUCTANCE OF CONTACT JOINTS, N.A.C.A. TN 3295, May 1955

8. Mc Adams, W. H. — HEAT TRANSMISSION, 3rd Edition, McGraw-Hill, 1954

9. Bridgman, P. W. — THE EFFECT OF PRESSURE ON THE THERMAL CONDUCTIVITY OF METALS, Proc. Am. Acad. Arts Sci., 57, 108 (1921-22)

10. Pagonis, G. A. — THE LIGHT METALS HANDBOOK, Vol. 1, D. Van Nostrand Co. Inc., 1954, pp 163-165

11. Plastics Catalogue Corporation — MODERN PLASTICS ENCYCLOPEDIA ISSUE, Sept. 1955, pp 90-91

12. A. S. T. M. — METALS HANDBOOK, 1948 Edition, p 822

APPENDIX I

TABLES OF EXPERIMENTAL DATA

Run	P	T_m	ΔT	dt/dx	h
1	50	250	15.0	246	1630
2.	200	142	5.3	115	2150
3	300	142	4.8	124	2560
4	100	143	7.0	111	1570
5	200	197	8.5	202	2350
6	200	202	9.0	204	2250
7	300	199	8.0	208	2590
8	100	207	11.3	202	1770
9	200	238	10.3	264	2535
10	200	234	10.5	250	2360
11	300	232	9.3	260	2775
12	100	239	13.0	252	1920
40	200	148	5.5	118	2140
41	300	145	4.4	124	2790
42	100	151	6.7	115	1710

Experimental data (air medium)

Table 4

Run	P	T_m	ΔT	dt/dx	h
14	200	149	10.4	126	1195
15	300	146	10.0	126	1254
16	100	151	11.8	124	1040
20	200	238	15.0	252	1665
21	300	236	10.8	266	2440
22	100	247	21.5	242	1114
24	200	205	14.0	192	1360
25	300	200	11.6	197	1683
26	100	210	21.0	194	917

Experimental data (vacuum medium)

Table 5

Run	P	T_m	ΔT	dt/dx	h
28	200	152	2.8	131	4660
29	300	152	2.7	134	4940
30	100	158	2.9	134	4570
31	200	205	3.7	203	5430
32	300	202	3.2	203	6300
33	100	212	4.2	206	4850
34	200	254	3.5	260	7350
35	300	251	3.0	268	8850
36	100	255	4.2	269	6350

Experimental data (helium medium)

Table 6

Thesis 32098
P47 Phillips
Effect of included media
on thermal conductance...